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DETERMINATION OF PARAMETERS OF NOCTILUCENT CLOUDS SURVEYED IN 1964

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ABSTRACT: The paper presents the theoretical basis of a stereophotogrammetrical survey of noctilucent clouds. It describes the methods of surveying used in 1964 and gives the results of the analysis of the photos obtained.

At the present time, the attention of many scientist in different countries of the world has been drawn to the question of the study of noctilucent clouds. This is understandable, since data from observations of noctilucent clouds allow study of the dynamics of the upper atmosphere. Moreover, a disclosure of the laws of formation of noctilucent clouds can help in investigating many physical processes. /33*

In that connection, information on definite spatial coordinates of noctilucent clouds or of an entire cloud formation, as well as its individual details, can help in a solution of the general problem of noctilucent clouds. Taking specific peculiarities of noctilucent clouds into consideration, a solution of the problem is possible only with the use of the photogrammetrical methods which are widely used for mapping the terrestial surface.

THEORETICAL BASIS OF THE METHOD

A solution to the problem can be found by two methods: photogrammetrical and stereophotogrammetrical. In the first case, the coordinates of the photographic images, derived from a certain base, are measured separately. With the measured coordinates, a calculation of horizontal and vertical angles at certain points is followed by a determination of direct intersection on the terrestial surface, as if taken from beyond the sphere. For derivation of the third coordinate - the height of a relatively level surface - trigonometric leveling formulas are used, applied to the case of great distances. Such a method was used by the author of this article in a study of the heights of noctilucent clouds in 1958, during the IGY.

In the second case, we are also concerned with direct intersection, but a measurement of the coordinates of the points from where the picture is taken and of the longitudinal parallaxes

* Numbers in the margin indicate pagination in the foreign text.

is produced jointly on stereocomparators with the use of a stereoscopic effect. One can then measure with great accuracy the angle of parallax at a certain point, which in linear measurement, as shown previously, is called longitudinal parallax.

This method has indubitable superiority in comparison with the first: the picture can be taken from short bases, and it is possible to obtain accurate identification of the same points in a pair of images, even in such undefined objects as the noctilucent clouds appear to be.

With the stereophotogrammetrical method and rectangular spatial coordinates, the following system is used: The surveying camera uses the foremost point of juncture of the object as the origin of the coordinates. Axis Y coincides with the optical axis: axis X is placed on the plane of the horizon of the left standpoint perpendicular to the first axis, and the axis Z runs vertically upward. /34

In this case, the following relate to elements of orientation:

a) Six elements of internal orientation -

$$f_l;\ f_r;\ x_l^0 z_l^0;\ x_r^0 z_r^0,$$

determining the origin of the coordinates of the left and right images of the stereo photograph;

b) The geodesic coordinates of the left end of the base are -

$$X_{l,r} Y_{l,r} Z_{l,r};$$

c) The surveying base b and its azimuth A;

d) The slope angles of the optical axes of the cameras ω_l and ω_r;

e) The angle of deviation of the optical axes from the normal to the base -

$$\phi_l,\ \phi_r;$$

f) The angle of convergence or divergence of the optical axes-

$$\gamma = \phi_r - \phi_l; \tag{1}$$

g) The angles of tilt κ_l, κ_r, which usually tend toward zero;

h) The overlap of the ends of the base Δh.

The simplest relationships between the spatial coordinates of the points of the photographed object and the coordinates of their perspective images would occur when the angles $\phi_l = \phi_r = 0°$ and $\omega_l = \omega_r = 0°$. In the theory of terrestrial stereophotogrammetrical photography this case is called "normal" and correlation of the coordinates is expressed in the following manner:

$$Y = \frac{b_0}{p} f,$$
$$X = \frac{b_0}{p} x_l, \qquad (2)$$
$$Z = \frac{b_0}{p} z_l.$$

However, in the practice of photographing noctilucent clouds a general case can also be encountered. The correlations of the coordinates will then have the form:

$$Y = \frac{(b_0 n - \Delta h x_r \sin\omega)}{m} (f\cos\omega - z_l \sin\omega),$$

$$X = \frac{(b_0 n - \Delta h x_r \sin\omega)}{m} x_l. \qquad (3)$$

$$Z = \frac{(b_0 n - \Delta h x_r \sin\omega)}{m} z_l (f\sin\omega + z_l \cos\omega),$$

where

$$n = x_r \sin(\phi + \gamma)\cos\omega + f(\phi + \gamma),$$

$$m = f^2 \sin\gamma\cos\omega - z_l f\sin\gamma\sin\omega + f x_l \cos\gamma - f x_r (\cos\gamma\cos^2\omega + \sin^2\omega) + x_r z_l \sin\omega\cos\omega(\cos\gamma - 1) + x_l x_r \sin\gamma\cos\omega.$$

These formulas can give a definite value for the spatial coordinates when the surface on which the camera base will stand is a plane. But in the photography of noctilucent clouds the surface of the Earth will differ greatly from a plane surface, and the /35 base may reach an order of magnitude of 50-100 km., while there are hundreds of kilometers between the standpoint and the points being measured.

In this case, we must analyze the written formulas with the aim of finding a possibility of using them in our study.

We will perform the given analysis using the example of the solution of the formulas of the normal case, and using geometric structures for the purpose, as seen in Figure 1.

We will take the point L as the left end of the base and the point R' as the right. Both of these points are located on the Earth's surface, with an average radius of curvature R. The distance between these points is equal to the arc of the circumference b, measured by the central angle γ'.

Let a simultaneous photographing of a certain point

in the noctilucent cloud be carried out with the cameras from these points; the focal distances of the cameras are equal. Let us call the images of this point on the photographs n_l and n_r. We will take the elements of orientation as being equal: $\phi_l = \phi_r = 0$, $\omega_l = \omega_r = 0$, $K_l = K_r = 0$. Hence, the optical angles of the cameras are normal to the normal base plane LCR'. To determine the spatial coordinates of the point N let us take point L as the origin of the coordinates. Then the direction of the optical axis will coincide with the direction of axis Y, while axis X will be tangent to arc b at point L. Axis Z will go in the direction of normal line LC. Axes Y and X are located on the plane of the horizon of point L. We will call /36
the coordinates of point n_l on the left photograph x_l and z_l.

In order to find the relationship between the coordinates X_l, Y_l, Z_l and x_l, z_l, let us do the following constructions. We will draw horizontal plane σ_l through point L. From point N we will draw normal line NC. We will call the point of intersection of that line with plane σ_l, N'_0, while the point of intersection with the surface of the sphere will be called N_0.

Obviously, the intersection of perpendicular line NC with plane σ_l will not form a right angle. Let us draw plane Q through point

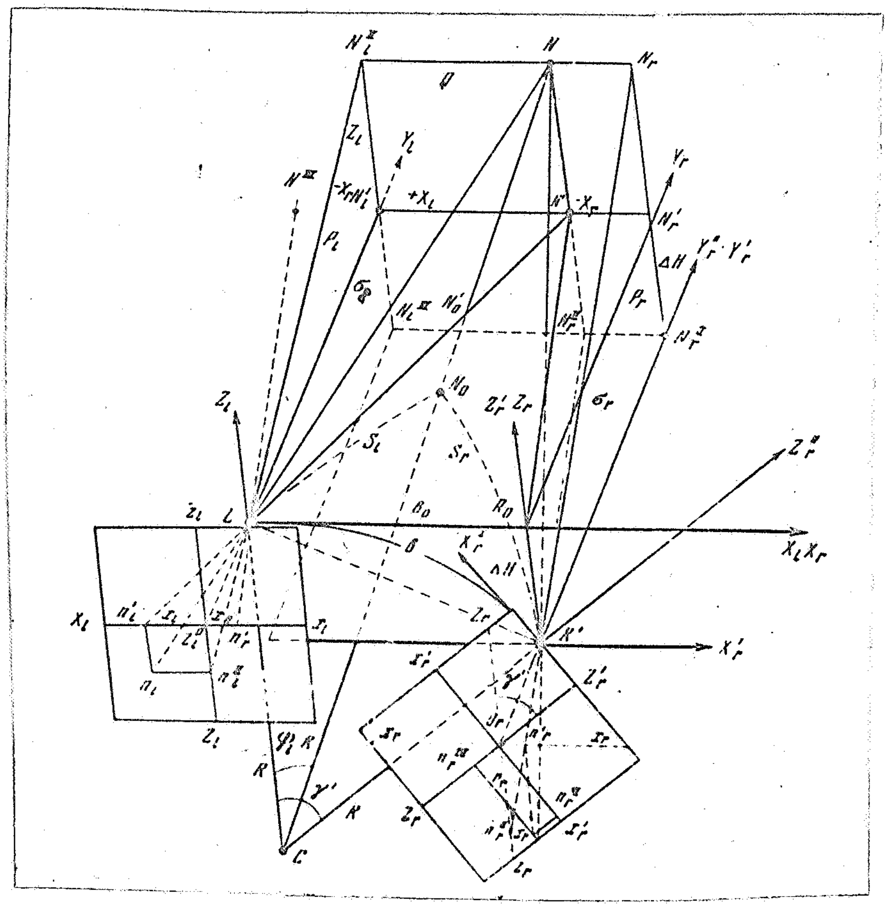

Fig. 1. Geometric Principle of Stereophotogrammetrical Intersection in Photographing Noctilucent Clouds.

N so that the latter is perpendicular to plane σ_l and parallel to the normal base plane LCR'. From point N let us drop perpendicular NN' to plane σ_l. Through line of LC and normal axis Y_l let us draw plane P_l which intersects planes σ_l and Q at right angles. From points N and NN' let us drop perpendiculars to plane P_l and call their bases N'_l and N''_l, respectively. Then segment $LN'_l = Y_l$, segment $N'_l N' = X_l$ and segment $N'_l N''_l = N'N = Z_l$. From the similarity of the right triangles $LN'_l N$ and $Ln'_l O_l$, and also of the triangles $LN'_l N''_l$ and $LO_l n''_l$, it follows that:

$$X_l = Y_l \frac{x_l}{f}, \qquad (4)$$

$$Z_l = Y_l \frac{z_l}{f}. \qquad (5)$$

In these equations we are concerned with three unknowns, and for a solution one must have three equations connecting each of these unknowns with another, independently of the measured values. We can get such an equation if we use the data from photographic measurements taken from the right-hand stand point.

For this purpose, let us look at the system of coordinates of the right-hand photograph. Just as for the left point, for the direction of axis Y''_r let us take optical axis $O_r R'$, which is assumed parallel to axis Y_l and lies on the plane of the horizon of the right-hand photograph. Axis X''_r is also located in this plane and its direction coincides with a line tangent to the arc of the circumference $R'bL$. The axis Z''_r runs along the normal CR'. The coordinating axes of the right-hand photograph X''_r and Z''_r, owing to the sphericity of the Earth, are not parallel to the corresponding axes of the left-hand picture, but are turned relative to one another by the value of the central angle γ'.

The coordinates of the point n_r in the right-hand photograph are respectively equal to

$$x'_r = O_r n'''_r, \quad z'_r = O_r n^{IV}_r.$$

To determine the spatial coordinates of point N from the origin at point R' let us rotate the system of coordinates $X''_r Z''_r$ around the axis Y''_r by the angle γ'. Moreover, let us call the new system of spatial coordinates Y'_r, X'_r, Z'_r, and the system of the coordinates of the right-hand photograph $x_r z_r$. The point n_r in this new system will have the following coordinates:

$$x_r = O_r n'_r,$$

$$z_r = O_r n''_r.$$

Now the systems of the coordinates of both photographs will be mutually parallel. Let us take the plane σ_r parallel to plane σ_l through point R' and axis Y''_r, and extend plane Q to intersect with plane σ_r. The intersection of these planes is shown in Figure 1 by the line N''_r, N''_l. Let us draw plane P_r parallel to plane P_l through point R' and axis Y'_r. This plane intersects the normal base plane LCR' on the line R_0R', along which the new axis Z'_r now lies. Segment LR_0 will appear as a projection of the base on the plane of the horizon σ_l. Calling it b_0, we will find that /37

$$b_0 = R\sin\gamma',$$

its value will differ from the base on the terrestrial surface b by no more than 1 or 2 meters.

Let us drop perpendiculars from point N to planes σ_r and P_r at points N''_r and N_r.

It follows from the similarity of the triangles $R'N''_r N''_r{}'$ and $R'O_rn'_r$, and also of the triangles $N_rN''_r R'$ and $R'O_rn''_r$ that

$$X'_r = Y'_r \frac{x_r}{f}, \tag{6}$$

$$Z'_r = Y'_r \frac{z_r}{f}. \tag{7}$$

We will shift the origin of the coordinates from point R' to point R_0, without changing direction. Then we will have a new system of coordinates

$$X_r = X'_r;\ Y_r = Y''_r;\ Z = Z'_r - \Delta h,$$

where

$$\Delta H = b\,\mathrm{tg}\frac{\gamma'}{2} \pm \Delta h.$$

Moreover, on condition that we make $Y_r = Y_l$, then

$$X_r = Y_l \frac{x_r}{f},$$

$$Z_r = Y_l \frac{z_r}{f} - \Delta H$$

It follows further from the similarity of the triangles $LN'N''$ and $Ln'_ln'_r$ that

$$\frac{X_l - X_r}{Y_l} = \frac{x_l - x_r}{f};$$

taking into consideration that

$$X_l - X_r = b_0,$$

while

$$x_l - x_r = p,$$

we obtained

$$Y_l = \frac{b_0}{p} f. \tag{8}$$

Substituting (8) into (4) and (5), and omitting the subscript l, we can write

$$X = \frac{b_0}{p} x_l, \tag{9}$$

$$Z = \frac{b_0}{p} z_l . \tag{10}$$

Comparing formulas (8), (9), and (10) with formulas (2), we see that they are identical. From this one could conclude that formulas written above for the terrestrial stereophotogrammetrical photograph under different conditions, for elements with internal orientation of the optical axes, can be used to determine spatial coordinates which are at a great distance from the point where the /38
objects are photographed.

To do this, one must rotate the systems of coordinates of the right-hand photograph in the stereomeasurements. First, the photographs in the cartridges of the apparatus are oriented according to the corresponding lines of the horizons. Then the reading κ_r is set by the scale "κ_r" , equal to the set value $\kappa_r + \gamma'$. It is easy to calculate the value:

$$\sin \gamma' = \frac{b_0}{R_m} . \tag{11}$$

Use of the formulas for a terrestrial stereophotogrammetrical photograph to determine the heights of noctilucent clouds allows us to find the latter only in relation to the plane of the horizon passing through the left-hand standpoint L. But we must know the height of the points in the projection on the terrestrial surface in the direction of the normal.

In accordance with Figure 2, the height of the point N above the level surface LN_0 will be equal to

$$NN_0 = H = N_0N_0' + N_0'N. \tag{12}$$

The segment N_0N_0' is none other than a correction for the curvature of the Earth, and one can calculate it according to the formula

$$N_0N_0' = R\frac{1 - \cos \psi_l}{\cos \psi_l} \tag{13}$$

The segment

$$N_0N = \frac{z}{\cos \psi_l} \quad . \tag{14}$$

Substituting (13) and (14) into (12), we obtain

$$H = \frac{R(1 - \cos \psi_l) + z}{\cos \psi_l} \quad .$$

Taking refraction into consideration, one can write /39

$$H = \frac{R(1 - \cos \psi_l) + z}{\cos \psi_l} - K \frac{D_l}{2R} \quad , \tag{15}$$

However, we do not know the value of the angle ψ_l, so, by using $\psi_l \approx \psi_l'$, we get an approximate formula for the heights

$$H' = \frac{R(1 - \cos \psi_l') + z}{\cos \psi_l'} - K \frac{D_l}{2R} \quad , \tag{16}$$

where the value of the angle ψ_l' is calculated according to the formula

$$\tan \psi_l' = \frac{\sqrt{y^2 + x^2}}{2\ R} \quad .$$

In determing the theoretical basis for the method, we will pause for a moment.

In the normal case, photographs of the directions of the optical axes coincide with the directions of the normals to the base. However, in other cases, the photographs of the directions of the optical axes will deviate from the normals by the angles ϕ. Since the angles ϕ are located on the corresponding planes of the horizons

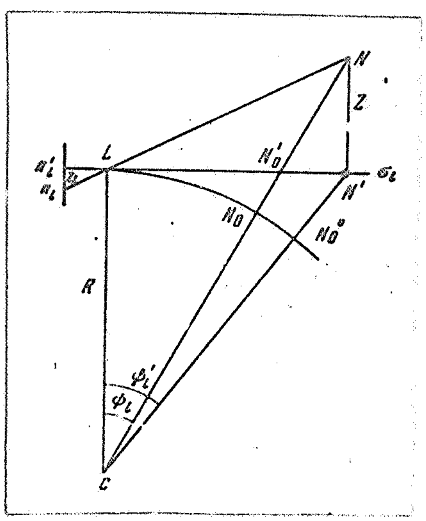

Fig. 2. Diagram of Determination of Absolute Heights of Noctilucent Clouds by Stereophotogrammetrical Elevators.

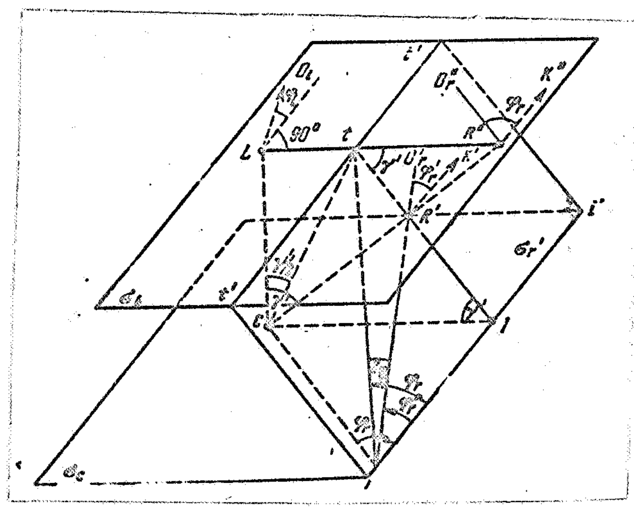

Fig. 3. Principal Diagram of Abnormal Angles of Inclination of the Right-Hand Optical Axis with Transition from the System of Coordinates of the Right-Hand Photograph to the Left.

of the left and right-hand standpoints, while the latter, as was noted, are not parallel to each other, then in projection of the angle ϕ from the right-hand plane of the horizon onto the left, the latter will be imaged on it with distortion. One can find the amount of distortion from the constructions shown in Figure 3.

Here the planes of the horizons at the points L and R' are called σ_l and σ_r. These planes intersect the line $t't'$ at the angle γ'. We will draw the plane σ_c parallel to the plane σ_c on the point of intersection of the C-normals to the terrestrial surface at the points L and R'. This plane intersects the plane $\sigma_{r'}$ in the line ii'. The normal base plane LCR' intersects plane σ_l on line LR'', plane $\sigma_{r'}$ on line tI, and plane σ_c on line CI. We will find the projection of point R' on plane σ_l by extending normal CR' to its intersection with line Lt at point R''. At points R' and R'' we will bring the normals to the normal base plane and call them $R'K'$ and $R''K''$. Let the optical axis $R'O_r'$ at the right-hand standpoint R' deviate from the normal $R'K'$ by angle ϕ_r'. We will construct an image of this line on plane σ_l in the following way. Let us extend the line $O_r'R'$ on plane σ_r to its intersection with line ii' at the point i and join this point to the point C. From point R'' on plane σ_l let us draw a line $R''O_r''$ parallel to line C_i. The line $R''O_r''$ forms angle ϕ_r with the normal $R''K''$, which will be relative to the projected angle ϕ_r and (in the general case) not equal to it.

We can then write

$$\delta_\phi = \phi_r - \phi_r' .$$

Let us connect the point i to point t, so that angle $tiI = \phi_r$. Moreover, angle CiI will also be equal to angle ϕ_r. We can readily see that angle $R'iI = \phi_r'$, since these angles are corresponding. From triangle $R'ti$ we have

$$\frac{R't}{\sin \delta_\phi} = \frac{t_i}{\sin (90 + \phi_r')} ,$$

or

$$\sin \delta_\phi = \frac{R't}{ti} \cos \phi_r'. \tag{18}$$

One can fine the value ti from the triangle tIi; /40

$$ti = \frac{R}{\sin\gamma' \sin(\phi_r' + \delta_\phi)}. \tag{19}$$

Moreover, we can write

$$R't = R \tan \frac{\gamma'}{2} . \tag{20}$$

Substituting (19) and (20) into (18), we get

$$\sin \delta_\phi = \tan \frac{\gamma'}{2} \sin \gamma' \sin (\phi'_r + \delta_\phi) \cos \phi'_r. \tag{21}$$

After some conversions we get

$$\tan \delta_\phi = \tan \frac{\gamma'}{2} \sin \gamma' (\sin \phi'_r + \cos \phi'_r \tan \delta_\phi) \cos \phi_r. \tag{22}$$

Noticing that

$$\tan \frac{\gamma'}{2} \sin \gamma' = 2 \sin^2 \frac{\gamma'}{2}, \tag{23}$$

we get the strict formula for the deviation of angles of inclination of the right-hand optical axis from the normal to the base of the photographic apparatus with their projection on the plane of the horizon of the left-hand standpoint:

$$\tan \delta_\phi = \frac{\sin^2 \frac{\gamma'}{2} \sin 2 \phi'_r}{1 - 2\sin^2 \frac{\gamma'}{2} \cos \phi'_r} \tag{24}$$

One can present a simplified formula for calculations in the following way:

$$\delta_\phi = \rho'' \sin^2 \frac{\gamma'}{2} \sin 2\phi'_r. \tag{25}$$

An analysis of formula (25) will show that maximum deviation will be at the angle ϕ'_r, equal to 45° or 135°, so that

$$\delta_{\phi\ max} = \rho'' \sin^2 \frac{\gamma'}{2} .$$

With $\gamma'_{max} = 53'$ - $\delta_{\phi\ max} = 12''$. With $\phi'_r = 0$, i.e. in the normal case of a photograph, $\delta_\phi = 0$.

With small angles of inclination on the order of $\phi'_r = 3°$, the value of deviation is $\delta_\phi = 0.07''$.

This analysis shows that small angles of inclination, the degree of deviation does not have to be taken into account. At large angles of inclination, one must make a correction in the direction of the optical axis of the right-hand camera.

As a result of this theoretical research, one can conclude that formulas (2) and (3) can be used successfully for determining the parameters of noctilucent clouds.

CALCULATION AND DETERMINATION OF PARAMETERS OF STEREOPHOTOGRAPHS

In accordance with the theoretical aspects of the method, in 1964, the Moscow Institute of Engineers in Geodesy, Aerial Photography, and Cartography (Ministry of Higher and Middle Special

Education of the Russian Soviet Federal Socialist Republic) together with the Institute of Physics and Astronomy (Academy of Sciences of the Estonian S.S.R.) conducted a stereophotogrammetrical survey of noctilucent clouds. In selecting the photographing-stations the researchers were influenced by the following considerations: /41

1) The length of the photographing base must correspond to the given accuracy of determination of the coordinates of the furthest points of the field of noctilucent clouds;

2) The direction of the base of the photograph must provide for maximum coverage of the zone of the occurrence of noctilucent clouds;

3) At each end of the base, there must be a good view of the horizon in the direction of the photograph;

4) The presence of clear indicators along the line of the horizon, which can be used for checking the directions of the optical axes of the cameras;

5) Direct telephone and radio communication between the ends of the base;

6) Reliable security of the photographic apparatus and its protection from unfavorable weather conditions;

7) The presence of power supplies for operating the apparatus.

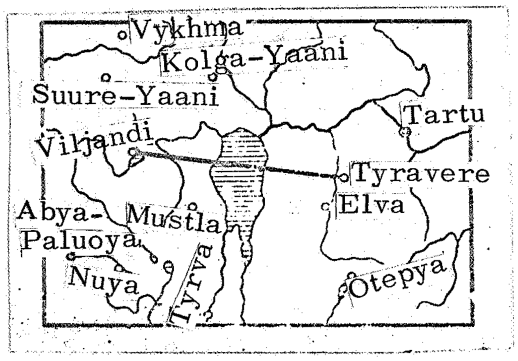

Fig. 4. Diagram of the Location of the Photographing Base.

In carrying out the photographic survey in 1964, all the given requirements were fulfilled, although the fulfillment of conditions for point 5 encountered a great many difficulties.

The connection between the points was set up with considerable delay, and it operated intermittently. As a result, some noteworthy occurrences of noctilucent clouds were missed.

A calculation of the length of the base from which the photographs are taken is made on the basis of a relation given by formula (2):

$$b = \frac{y^2 mp}{m_y f}.$$

With y = 500 km., mp = ±0.05 mm., f = 100 mm:

$$\frac{m_y}{y} = \frac{1}{1000},\quad b = \frac{500 \cdot 500 \cdot 10 \cdot 5}{1 \cdot 100 \cdot 100} \approx 75 \text{ km}.$$

However, considering that clouds over the territory of the Estonian SSR. can appear very close to the zenith, i.e. at distances of, for example, Y_{min} = 200 km., and that $b_{max} = y_{min}/4$ is limited by the physiological conditions of stereoscopy, the value of the base was taken as equal to

$$b = \frac{200}{4} = 50 \text{ km.}$$

Since the clouds appear in the zone of the crepuscular segment, i.e. in the northern part of the sky, the direction of the base must be located parallel to the lines of latitude. These conditions were satisfied by two points, the city of Viljandi and the Tyravere Observatory. A diagram of the position of the base is shown in Figure 4.

To determine the dimensions of the base from which the pictures were taken, and also of the directions of the optical axes, geodesic connections of the ends of the base to the points of triangulation were made.

As a result of the field and camera geodesic operations, the following parameters of the photograph were obtained.

The length of the base b = 52012 meters. The azimuths of the base are: direct - A_{tr} = 101° 44′22″, reverse - A_{rl} = 282° 28′ 38″. /42

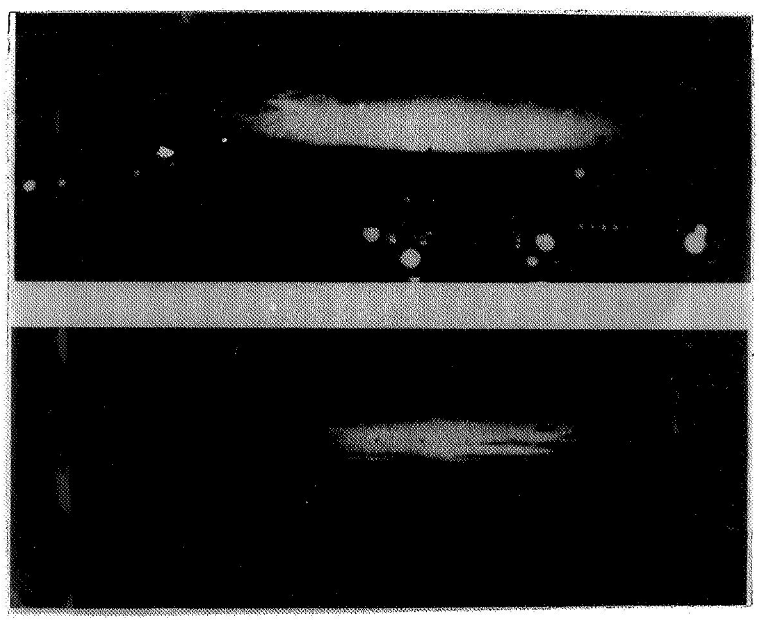

Fig. 5. Stereopair No. 14: Noctilucent Clouds, Taken on August 2, 1964.

The azimuths of the optical axes are:

$$A_{0l} = 11°24'20''$$

$$A_{0l} = 11°49'11''.$$

The angles of deviation of the optical axes from the normals to the base are:

$$\phi_l = +\ 0°20'00'',$$

$$\phi_r = +\ 0°39'27''.$$

The angle of convergence of the optical axes

$$\gamma = \phi_r - \phi_l = +\ 0°19'27''.$$

The angles of inclination of the optical axes of the cameras are

$$\omega_l = \omega_r = +\ 30°.$$

The tilt angles are:

$$k_l = k_r = 0°.$$

The latitude of the left-hand standpoint is

$$B = 58.4°.$$

The longitude of the left-hand standpoint

$$L = 25.6°.$$

PHOTOGRAPHIC APPARATUS

Proceeding from maximum coverage of the glowing sector with identical directions of the optical axes, two AFA-41/10 cameras with focal lengths of 98.64 and 98.92, respectively, were chosen.

These cameras are completely automatic and are controlled remotely from the master instruments. The cameras were supplied with MRO-2 objectives, with a focal distance of 100 mm. The relative aperture of the objective is 1:8.

The angle formed by the field of vision with the sides of a photograph measuring 18x18 cm. is equal to 84°. The coefficient of transmissivity of the objective is at least 0.65. The resolving power of the aerial camera is at least 37 lines/mm (at the edges, 10 lines/mm.).

The camera was supplied with the following light filters:

USS-18, OS-14, KS-14, and colorless glass; the light filters were supplied with shades for adjusting the exposure.

The shutters of the cameras are central, using the "Vyertiyorokh" system. Effective exposures can vary within a range of 1/60 to 1/500 sec. However, considering the low luminosity of noctilucent clouds, the drive mechanism of the shutters was rebuilt to increase the exposures. The shutter is switched on by a special toggle switch. The electrical impulse lights lamps on the recording instruments. The film advances automatically each time the shutter closes. The film is held in place by clamping the leveling board of the cartridge to the plane of the mounting frame, which was mounted in the camera in the form of a piece of a plane-parallel glass. The glass was inserted for calibrating the optical system of the camera. Its surface was marked all over with small crosses at intervals of 10 mm. Knowing the distances between these crosses, we can allow for distortion of the negative material in processing the photographs.

Moreover, the coordinating points are shown on the sides of the frame, and the position of the main point of the camera appears in the center.

In the interval between cloud photographs, a clock with a sweep second hand is photographed; which allows synchronization of photographs, measuring of photographs, focal distance, number of the camera, and marks indicating the beginning of photography and indi- /43
cating every fifth picture, as well as an arrow indicating the frame to which the indicators have advanced. Each camera is equipped with two film holders. The first is a cartridge with a capacity of 60 meters of film, and can take 270 pictures; the second, with a capacity of 120 meters of film, can take around 540 pictures. The film can be used in perforated or unperforated lengths up to a width of 19 cm. The required supply of d.c. current is 27±10% volts. The bases of the cameras allow them to be tilted to any angle of inclination and turned along the azimuth at angles of ±10° from the original position. The lower half of the setup is fastened on supports which have four adjusting screws for leveling the camera and for eliminating the tilt angle; this is done with the help of two mutually perpendicular levels. The levels are fastened to a special base which is fixed to the body of the camera. Orientation of the cameras to the azimuth is done with the help of a special orienting device.

PROCESSING STEREOPHOTOGRAMMETRICAL PICTURES AND ANALYSIS OF THE RESULTS OBTAINED

To photograph noctilucent clouds, we used "Izopankhrom" film, Type 13, with a sensitivity of 1900 units GOST-0.85, issued in March, 1964. The value of the exposure was determined experimentally and was changed depending on the setting angle of the Sun, varying from 40 sec. to 1 min.

We succeeded in obtaining the first stereophotogrammetrical pictures of the appearance of noctilucent clouds on August 2, 1964.

We obtained a total of 9 stereopairs in a 5-minute interval.

Stereopair No. 10 was obtained at 0245 standard time at t = 1 min; stereopair No. 11 at 0250, t = 1 min; stereopair No. 12 at 0255, t = 50 sec; stereopair No. 13 at 0300, t = 50 sec; stereopair No. 14 at 0305, t = 50 sec; stereopair No. 16 at 0315 and stereopair No. 17 at 0320, t = 40 sec. Stereopair No. 14 appears in Figure 5.

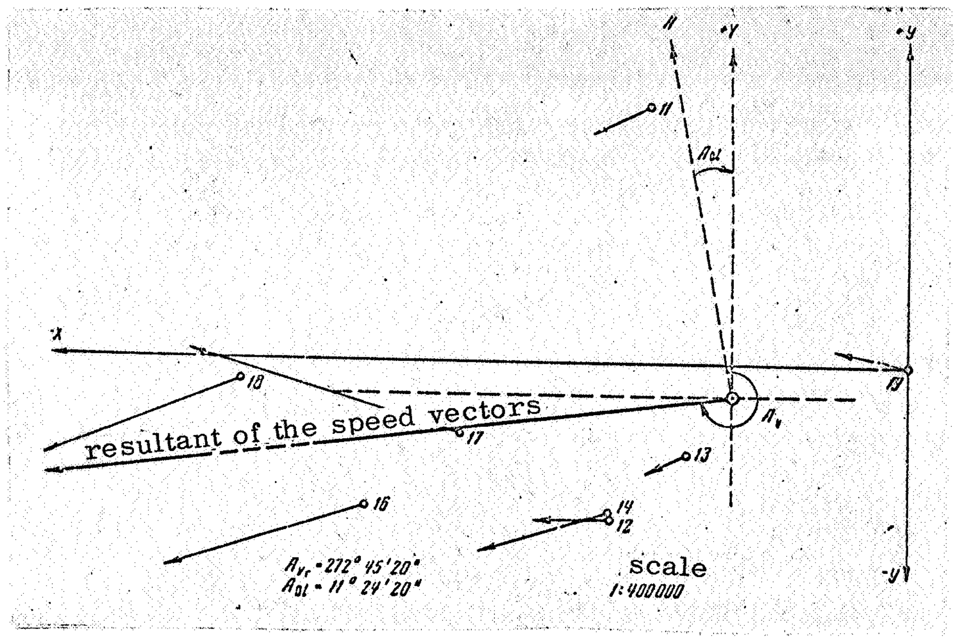

Fig. 6. Diagram of the Vectors of the Rate of Movement of Distant Points in a Field of Noctilucent Clouds.

TABLE: COMPOSITE TABLE OF DETERMINATION OF PARAMETERS OF NOCTILUCENT CLOUDS COORDINATES /44

No. of pairs	No. of points	coordinates								
		Y	X	H	ΔY	ΔX	ΔH	ΔD	V_r	V_B
		1	2	3	4	5	6	7	8	9
10	11	607,7	—70,0	79,6						
	12	555,6	—75,4	75,6						
	13	564,3	—64,5	82,0						
	14	556,2	—75,5	85,5						
	15	561,4	—43,2	82,0						
	4	606,1	—83,5	89,1						
	5	577,0	—62,2	86,9						
	6	560,7	—93,3	88,7						
	7	604,0	—82,4	88,4						
	8	608,0	—59,6	89,7						

No. of pairs	No. of points	coordinates								
		Y	X	H	ΔY	ΔX	ΔH	ΔD	V_{Γ}	V_{B}
		1	2	3	4	5	6	7	8	9
11	11	604,1	—77,8	82,2	—3,6	—7,8	+2,6	8,6	29	9
	12	555,5	—85,7	78,6	—0,1	—10,3	+2,9	10,3	35	10
	13	561,8	—69,3	82,6	—2,5	—4,8	+0,5	5,4	18	2
	14	551,3	—92,4	82,5	—4,9	—16,9	—3,0	17,6	59	10
	15	568,8	—45,4	78,0	+7,4	—2,2	—3,9	7,7	26	13
	1	596,5	—168,4	75,4						
	2	556,4	—159,0	80,4						
	6	579,6	—54,1	82,8						
	7	555,3	—52,1	84,2						
	8	577,1	—68,4	87,4						
13	15	567,2	—223,2	85,9						
	16	549,7	—143,8	84,9						
	17	559,6	—132,1	76,5						
	18	[illegible]	—160,5	83,7						
	19	[illegible]	—74,3	85,7						
	1	538,2	—63,8	77,2						
	2	565,6	—63,8	79,1						
	3	552,2	—62,8	79,4						
	4	584,4	—64,1	85,0						
	5	551,0	—62,7	84,5						
	8	556,9	—76,6	75,3						
	9	572,4	—79,0	82,3						
	10	552,7	—76,6	82,9						
	11	542,8	—75,5	83,8						
14	15	561,7	—234,3	84,2	—5,5	—11,1	—1,7	12,4	41	6
	16	540,8	—170,1	84,8	—8,9	—26,3	0,0	27,8	93	0
	17	569,9	—167,1	79,5	+10,3	—35,0	+3,1	36,5	122	10
	18	555,6	—186,8	80,6	—10,7	—26,3	—3,2	28,4	95	11
	19	571,6	—84,4	89,4	+2,4	—10,1	+3,8	10,4	35	12
	1	580,2	—120,0	81,8						
	2	576,5	—136,5	89,9						
	3	602,1	—170,1	83,4						
	4	565,7	—197,5	84,2						
	5	580,7	—241,8	87,2						
14	6	540,3	—167,9	85,1						
	7	578,4	—163,5	81,7						
	8	554,5	—163,6	80,2						
	9	547,1	—173,2	89,0						
	10	574,9	—198,6	78,6						
	11	564,8	—235,6	84,7						
	12	560,9	—208,8	79,6						
	13	569,0	—192,4	83,2						
	13'	556,1	—188,5	80,1						
	14	562,3	—189,1	81,1						
	14'	549,6	—185,2	74,8						

No. of pairs	No. of points	coordinates								
		Y	X	H	ΔY	ΔX	ΔH	ΔD	$V_{г}$	$V_{в}$
		1	2	3	4	5	6	7	8	9
16	1	573,3	−100,3	89,9						
	2	568,2	−98,7	80,9						
	3	498,0	−88,9	93,0						
	4	588,7	−175,5	82,4						
	5	505,4	−153,3	82,6						
	6	507,0	−167,5	73,4						
	7	444,9	−146,5	90,6						
	8	551,9	−210,6	88,4						
	9	551,8	−153,6	80,5						
	10	459,3	−122,6	83,4						
17	1	583,5	−119,2	84,2						
	2	575,0	−117,7	88,5						
	3	580,3	−187,2	94,0						
	4	594,8	−216,9	84,0						
	5	605,6	−212,6	79,4						
	6	605,0	−227,0	80,4						
	7	597,8	−228,3	89,8						
	8	601,1	−197,8	78,2						
	9	592,3	−169,4	87,5						
	10	613,0	−167,4	79,8						

A measurement of the coordinates of the points of noctilucent clouds was performed on the stereocomparator with four-fold binocular magnification. /45

In all, 85 points in 7 stereopairs were measured. The processing was done according to formula (3). The spatial coordinates of these points are given in the table.

Analyzing the given results of the parameters of noctilucent clouds, the following should be noted.

The maximum distance of the points of occurrence of noctilucent clouds amounted to Y_{max} = 613 km.; the minimum was Y_{min} = 450 km; the length along the front could be measured only by the points arranged to the left of the optical axis. On the right of the optical axis, the image of the cloud showed no details at all, and it looked like a flare bright spot, which did not allow corresponding measurements to be carried out. Thus, the measured distance along the front was 270 km. As for height, the measured points /46
oscillated from H_{max} = 90.6 km to H_{min} = 73.4 km.

The accuracy of the results obtained is characterized by the following mean square errors of the coordinates determined: m_Y = ±3 km; m_x = ±1 km; m_H = ±0.8 km. The speed rate of movement of the points on the noctilucent clouds is characterized by the values shown in columns 6, 8, and 9 of the Table. The maximum rate of movement in the horizontal plane is $V_{r\max} = 122$ m/sec, $V_{r\min} = 18$ m/sec. The direction of horizontal variation is shown in Figure 6. The resultant direction of the speed vector is $A_{V_r} = 272°45'20''$, i.e. the cloud moved in a southwesterly direction.

Besides horizontal deviation, the points have a vertical speed as well: $V_{B_{\max}} = 13$ m./sec, $V_{B_{\min}} = 0$.

From the sign of ΔH, we can also judge the direction of vertical speed.

Our method makes it relatively simple to solve all problems connected with determination of the parameters of noctilucent clouds.

The one drawback is the great volume of calculations. However, a program of computer calculation is now being worked out, so as not to limit the number of measured points in a field of noctilucent clouds.

This fact also permits describing the photographed field with the help of isohypses.

In conclusion, I wish to express my deep gratitude to C.I. Villmann for his great help in organizing and designing the experimental aspects of this method. I also express my appreciation to a student in the Department of Aeronautics at Moscow University, V.N. Shutov, and his collaborator at the Institute of Physics and Astronomy, Ya. F. Lokk, for active assistance in the photographic portion of the work.

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